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( THERMODYNAMIC PROPERTIES  
OF CESIUM UP TO 1500° K )

*by Sheldon Heimerl*  
*Lewis Research Center*  
*Cleveland, Ohio*

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By Sheldon HeimeI

Lewis Research Center  
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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# THERMODYNAMIC PROPERTIES OF CESIUM UP TO 1500° K

by Sheldon HeimeI

Lewis Research Center

## SUMMARY

Consistent tables of thermodynamic properties of elemental cesium were compiled for both the pure species and the equilibrium vapor on the saturation line using selected values of 10 500 calories per mole for the heat of dissociation of dimer and -18 920 calories per mole for the heat of condensation of monomer. The equilibrium vapor properties and properties of condensed cesium (Cs) are given to 1500° K, while properties of gaseous monomer and dimer are given to 2500° K.

The table of mixture properties on the saturation line gives the following thermodynamic functions: temperature  $T$ , total vapor pressure  $P$ , weight fraction of dimer in vapor  $x_2$ , molecular weight  $M_g$ , specific volume  $v$ , density  $\rho$ , enthalpy of condensed phase  $h_c$ , enthalpy of vaporization  $\Delta h_{vap}$ , enthalpy of vapor  $h_g$ , entropy of condensed phase  $s_c$ , entropy of vaporization  $\Delta s_{vap}$ , entropy of vapor  $s_g$ , and heat capacities (equilibrium and frozen)  $(c_p)_{eq}$  and  $(c_p)_{fr}$ . Assigned enthalpies are relative to enthalpy of the crystal at 298.15° K, which is taken to be zero. The tables of properties for the pure species give the following thermodynamic functions for the standard state: heat capacity at constant pressure  $C_p^0$ , sensible enthalpy  $H_T^0 - H_O^0$ , entropy  $S_T^0$ , sensible free energy  $F_T^0 - H_O^0$ , the sum of sensible enthalpy at  $T^0$  K and chemical energy at 0° K  $H_T^0$ , and values of enthalpy changes and logarithms of the equilibrium constants. The latter two functions are given for the reactions of formation of  $Cs(c)$ ,  $Cs_1(g)$ , and  $Cs_2(g)$  from the assigned reference state  $Cs(c)$  ( $(\Delta H_T^0)_f$  and  $\log_{10} K_f$ ) and from  $Cs_1(g)$  ( $\Delta H_T^0$  and  $\log_{10} K$ ).

Thermodynamic functions for the gases were generated from atomic and molecular data, whereas the functions of the condensed phase were based on selected experimental data that were smoothed and made self-consistent.

end

TABLE I. - THERMODYNAMIC PROPERTIES  
OF CESIUM (CRYSTAL) UP TO 100° K

T, °K	C <sub>p</sub> <sup>o</sup> , cal/(mole)(°K)	H <sub>T</sub> <sup>o</sup> - H <sub>O</sub> <sup>o</sup> , cal/mole	S <sub>T</sub> <sup>o</sup> , cal/(mole)(°K)	-(F <sub>T</sub> <sup>o</sup> - H <sub>O</sub> <sup>o</sup> ), cal/mole
5	0.746	1.2	0.3342	0.5
10	2.379	9.0	1.3539	4.5
15	3.719	23.9	2.5835	14.9
20	4.680	44.5	3.7993	31.5
25	5.110	69.1	4.8935	53.3
30	5.385	95.3	5.8513	80.2
35	5.558	122.7	6.6955	111.6
40	5.668	150.8	7.4454	147.0
45	5.741	179.4	8.1174	185.9
50	5.795	208.2	8.7252	228.1
55	5.842	237.3	9.2798	273.1
60	5.888	266.6	9.7901	320.8
65	5.933	296.2	10.2631	370.9
70	5.977	325.9	10.7044	423.4
75	6.016	355.9	11.1182	477.9
80	6.049	386.1	11.5076	534.5
85	6.075	416.4	11.8751	593.0
90	6.097	446.8	12.2230	653.2
95	6.122	477.4	12.5533	715.2
100	6.160	508.1	12.8682	778.7

tables III (Cs<sub>1</sub>) and IV (Cs<sub>2</sub>), data are tabulated at 100° intervals from 0° to 2500° K for the ideal gases. Table V (p. 8) contains the molecular constants used to calculate thermodynamic functions for dimeric cesium.

Table VI (p. 8) contains recommended boiling points of liquid cesium calculated from the final set of thermodynamic properties. These boiling points correspond to pressures from 10<sup>-8</sup> to 10 atmospheres at every power of 10. For comparison, boiling points obtained from equation (33) are also given.

Table VII (p. 9) gives the following thermodynamic properties of the equilibrium gaseous mixture on the saturation line: T, P, p<sub>1</sub>, p<sub>2</sub>, x<sub>2</sub>, M<sub>g</sub>, v, ρ, h<sub>c</sub>, Δh<sub>vap</sub>, h<sub>g</sub>, s<sub>c</sub>, Δs<sub>vap</sub>, s<sub>g</sub>, (c<sub>p</sub>)<sub>eq</sub>, and (c<sub>p</sub>)<sub>fr</sub>. The values of P, p<sub>1</sub>, p<sub>2</sub>, v, and ρ are given in floating-point notation, where the decimal number is to be multiplied by

10 raised to the power of the sign and the two digits following the letter E; for example, 0.100000E-03 is 0.100000×10<sup>-3</sup> = 0.0001.

### Assigned Reference State

The assigned reference state is Cs (crystal, liquid). The crystal is the reference state up to the melting point, and the liquid phase is the reference state above the melting point.

### Assigned Enthalpy Values H<sub>T</sub><sup>o</sup>

For some applications (ref. 1), it is convenient to combine sensible enthalpy H<sub>T</sub><sup>o</sup> - H<sub>O</sub><sup>o</sup> and chemical energy H<sub>O</sub><sup>o</sup> into one numerical value, H<sub>T</sub><sup>o</sup>. The arbitrary base

TABLE II. - THERMODYNAMIC PROPERTIES OF CESIUM (CRYSTAL, LIQUID)

T, °K	$C_p^0$ cal (mole)(°K)	$H_T^0 - H_O^0$ cal/mole	$S_T^0$ cal (mole)(°K)	$-(F_T^0 - H_O^0)$ cal/mole	$H_T^0$ cal/mole	Formation from assigned reference state		Formation from gaseous atoms	
						$(\Delta H_T^0)_f$ cal/mole	$\log_{10} K_f$	$\Delta H_T^0$ cal/mole	$\log_{10} K$
0	-----	0	0	0	-1807.2	0	-----	-1892.0	-----
100	6.160	508.1	12.8682	778.7	-1299.1	0	0	-1890.7	35.1543
200	6.260	1144.1	17.2607	2308.0	-863.1	0	0	-1876.5	15.5486
298.15	6.953	1807.2	19.9532	4141.8	0.0	0	0	-1859.0	3.9232
300	6.960	1820.1	19.9962	4178.8	12.9	0	0	-1859.3	8.7392
331.8	6.567	1832.6	20.0379	4214.8	25.4	0	0	-18586.8	8.5584
331.8	7.455	2352.7	21.7612	4214.8	545.5	0	0	-1806.7	3.5584
400	7.455	3084.8	23.8613	6459.7	1277.6	0	0	-17622.4	5.4664
500	7.455	3830.3	25.5248	8932.1	2023.1	0	0	-17573.8	3.5315
600	7.455	4575.8	26.8840	11594.6	2768.6	0	0	-17325.1	2.2509
700	7.455	5321.3	28.0332	14301.9	3514.1	0	0	-17076.4	1.3445
800	7.455	6066.8	29.0287	17156.1	4259.6	0	0	-16827.7	0.7327
900	7.455	6812.3	29.9067	20103.8	5005.1	0	0	-16575.0	0.1956
937.71	7.455	7093.4	30.2127	21237.4	5286.2	0	0	-16485.2	0.3341
1000	7.455	7557.8	30.6922	23134.4	5750.6	0	0	-16330.3	-0.2341
1100	7.455	8303.3	31.4027	26239.7	6496.1	0	0	-16081.7	-0.5261
1200	7.455	9048.8	32.0514	29412.9	7241.6	0	0	-15833.1	-0.7934
1300	7.455	9794.3	32.6481	32648.3	7997.1	0	0	-15584.6	-1.0105
1400	7.455	10539.8	33.2006	35941.0	8732.6	0	0	-15336.4	-1.1962
1500	7.455	11285.3	33.7150	39287.1	9478.1	0	0	-15088.7	-1.3545

<sup>a</sup>Melting point.<sup>b</sup>Normal boiling point to equilibrium mixture.

TABLE III. - THERMODYNAMIC PROPERTIES OF Cs<sub>1</sub> (GAS)

T, °K	C <sub>p</sub> <sup>o</sup> , cal (mole)(°K)	H <sub>T</sub> <sup>o</sup> - H <sub>O</sub> <sup>o</sup> , cal/mole	S <sub>T</sub> <sup>o</sup> , cal (mole)(°K)	-(F <sub>T</sub> <sup>o</sup> - H <sub>O</sub> <sup>o</sup> ), cal/mole	H <sub>T</sub> <sup>o</sup> , cal/mole	Formation from assigned reference state		Formation from gaseous atoms	
						(ΔH <sub>T</sub> <sup>o</sup> ) <sub>f</sub> , cal/mole	log <sub>10</sub> K <sub>f</sub>	ΔH <sub>T</sub> <sup>o</sup> , cal/mole	log <sub>10</sub> K
0	-----	C	-----	0	17112.8	18920.0	-----	0	-----
100	4.9681	496.8	36.5168	3154.9	17609.6	18908.7	-36.1548	0	0
200	4.9681	993.6	39.9605	6998.5	18105.4	18769.5	-15.5486	0	0
298.15	4.9681	1481.3	41.9442	11024.4	18594.0	18594.0	-8.9232	0	0
300	4.9681	1490.4	41.9749	11102.0	18603.2	18590.3	-8.7392	0	0
301.8	4.9681	1499.4	42.0046	11177.6	18612.2	18606.7	-8.6584	0	0
400	4.9681	1987.3	43.4042	15374.4	19100.0	17822.4	-5.4664	0	0
500	4.9681	2484.1	44.5128	19772.3	19596.8	17573.8	-3.5315	0	0
600	4.9681	2980.9	45.4186	24270.2	20093.7	17325.1	-2.2598	0	0
700	4.9682	3477.7	46.1844	28851.4	20590.5	17076.4	-1.3645	0	0
800	4.9682	3974.5	46.8478	33503.7	21087.3	16827.7	-0.7027	0	0
900	4.9682	4471.3	47.4330	38218.3	21594.1	16579.0	-0.1956	0	0
937.71	4.9682	4656.7	47.6369	40010.9	21771.5	16485.2	-0.0341	0	0
1000	4.9683	4968.2	47.9364	42988.3	22080.9	16330.3	0.2041	0	0
1100	4.9686	5465.0	48.4300	47808.0	22577.8	16081.7	0.5261	0	0
1200	4.9654	5961.9	48.8623	52672.9	23074.7	15833.1	0.7904	0	0
1300	4.9712	6458.9	49.2601	57579.3	23571.7	15584.6	1.0105	0	0
1400	4.9749	6956.2	49.6287	62524.0	24069.0	15336.4	1.1962	0	0
1500	4.9814	7454.0	49.9721	67504.2	24566.7	15088.7	1.3545	0	0
1600	4.9915	7952.6	50.2939	72517.7	25065.4	0	0	0	0
1700	5.0079	8452.6	50.5970	77562.3	25565.3	0	0	0	0
1800	5.0307	8954.4	50.8839	82636.5	26067.2	0	0	0	0
1900	5.0616	9459.0	51.1566	87738.6	26571.7	0	0	0	0
2000	5.1025	9967.1	51.4173	92867.4	27079.9	0	0	0	0
2100	5.1541	10479.8	51.6674	98021.8	27592.6	0	0	0	0
2200	5.2175	10998.3	51.9086	103200.6	28111.1	0	0	0	0
2300	5.2936	11523.8	52.1422	108403.2	28636.5	0	0	0	0
2400	5.3832	12057.5	52.3693	113628.8	29170.3	0	0	0	0
2500	5.4867	12600.9	52.5911	118876.9	29713.6	0	0	0	0

<sup>a</sup>The reference element is crystal cesium up to 301.8° K and liquid cesium above 301.8° K.

TABLE IV. - THERMODYNAMIC PROPERTIES OF Cs<sub>2</sub> (GAS)

T, °K	C <sub>p</sub> <sup>o</sup> , cal (mole)(°K)	H <sub>T</sub> <sup>o</sup> - H <sub>O</sub> <sup>o</sup> , cal/mole	S <sub>T</sub> <sup>o</sup> , cal (mole)(°K)	-(F <sub>T</sub> <sup>o</sup> - H <sub>O</sub> <sup>o</sup> ), cal/mole	H <sub>T</sub> <sup>o</sup> , cal/mole	Formation from assigned reference state		Formation from gaseous atoms	
						(ΔH <sub>T</sub> <sup>o</sup> ) <sub>f</sub> , cal/mole	log <sub>10</sub> K <sub>f</sub>	ΔH <sub>T</sub> <sup>o</sup> , cal/mole	log <sub>10</sub> K
0	---	0	---	0	23725.6	27340.1	---	-10500.0	---
100	8.9436	843.2	57.9961	4956.4	24568.8	27167.1	-52.3208	-10650.3	19.9859
200	9.0457	1743.6	64.2330	11103.0	25469.2	26795.5	-22.7862	-10743.6	8.3110
298.15	9.1202	2635.4	67.8598	17597.0	26361.0	26361.0	-13.2133	-10827.1	4.4332
300	9.1215	2652.3	67.9162	17722.6	26377.9	26362.1	-13.0941	-10828.6	4.3842
301.8	9.1227	2668.7	67.9707	17844.9	26394.3	26363.3	-12.9797	-10830.0	4.3372
400	9.1893	3567.8	70.5456	24652.0	27293.4	24738.2	-8.5271	-10906.7	2.4057
500	9.2572	4490.1	72.6074	31813.6	28215.7	24169.6	-5.8528	-10978.0	1.2102
600	9.3259	5419.3	74.3012	39161.5	29144.9	23607.7	-4.1114	-11042.4	0.4083
700	9.3959	6355.4	75.7441	46665.5	30081.0	23032.8	-2.8967	-11100.0	-0.1578
800	9.4674	7298.5	77.0034	54304.2	31024.1	22504.9	-2.0073	-11150.5	-0.6319
900	9.5402	8248.9	78.1227	62061.5	31974.5	21964.3	-1.3321	-11193.7	-0.9410
937.71	9.5681	8609.2	78.5148	65015.0	32334.8	21762.3	-1.1186	-11208.1	-1.0534
1000	9.6146	9206.6	79.1317	69925.1	32937.2	21431.0	-0.8051	-11229.6	-1.2132
1100	9.6905	10171.8	80.0516	77884.9	33697.4	20905.3	-0.3843	-11258.1	-1.4366
1200	9.7679	11144.7	80.8981	85932.9	34870.3	20387.2	-0.0424	-11279.0	-1.6232
1300	9.8468	12125.5	81.6830	94062.5	35851.1	19876.9	0.2397	-11292.3	-1.7813
1400	9.9273	13114.2	82.4157	102267.8	36839.8	19374.6	0.4754	-11298.2	-1.9169
1500	10.0053	14111.0	83.1034	110544.1	37836.6	18880.4	0.6745	-11296.9	-2.0345
1600	10.0828	15116.1	83.7520	118887.2	38841.7			-11289.1	-2.1373
1700	10.1779	16129.6	84.3664	127293.4	39855.2			-11275.4	-2.2280
1800	10.2646	17151.7	84.9506	135759.4	40877.3			-11257.1	-2.3085
1900	10.3527	18182.6	85.5080	144282.6	41908.2			-11235.3	-2.3803
2000	10.4425	19222.3	86.0413	152860.2	42947.9			-11211.8	-2.4449
2100	10.5337	20271.1	86.5530	161490.1	43996.7			-11188.5	-2.5032
2200	10.6266	21329.1	87.0451	170170.2	45054.7			-11167.5	-2.5560
2300	10.7209	22396.5	87.5190	178898.6	46122.1			-11151.0	-2.6042
2400	10.8168	23473.3	87.9779	187673.6	47198.9			-11141.6	-2.6483
2500	10.9143	24559.9	88.4214	196493.6	48285.5			-11141.8	-2.6889

<sup>a</sup>The reference element is crystal cesium up to 301.8° K and liquid cesium above 301.8° K.



TABLE V. - MOLECULAR

CONSTANTS FOR DI-

ATOMIC CESIUM

Molecular weight	265.82
Symmetry number	2
Electronic state <sup>a</sup>	$1\Sigma$
Statistical weight	1
$\omega_e$ , cm <sup>-1</sup> <sup>a</sup>	41.990
$\omega_e x_e$ , cm <sup>-1</sup> <sup>a</sup>	0.08005
$\omega_e y_e$ , cm <sup>-1</sup> <sup>a</sup>	-0.0001643
$B_e$ , cm <sup>-1</sup> <sup>b</sup>	0.01272
$\alpha_e$ , cm <sup>-1</sup> <sup>b</sup>	0.000035
$D_e$ , cm <sup>-1</sup> <sup>b</sup>	$0.467 \times 10^{-8}$

<sup>a</sup>Constant from ref. 10.<sup>b</sup>Constant from ref. 11.

TABLE VI. - BOILING POINTS OF LIQUID

CESIUM FROM  $10^{-8}$  TO 10 ATMOSPHERES

$\log_{10} P_{\text{atm}}$	Boiling points, °K	
	Recommended	From equation (33) <sup>a</sup>
-8	317.8	317.8
-7	345.8	345.8
-6	379.2	379.4
-5	420.1	420.3
-4	471.2	471.4
-3	537.0	537.2
-2	625.0	625.0
-1	749.1	748.7
0	937.7	937.3
1	1264.0	1264.5

$$^a \log_{10} P_{\text{atm}} = \frac{-4053.30}{T} + 7.04453 - 0.915282 \log_{10} T.$$

for assigning values to the enthalpy of Cs(c) was a value of zero at 298.15° K. Since table II gives  $(H_{298.15}^O - H_{O}^O)_{\text{Cs(c)}} = 1807.2$  calories per mole, then  $(H_{O}^O)_{\text{Cs(c)}} = -1807.2$  calories per mole. From table II,  $(\Delta H_{O}^O)_c = (H_{O}^O)_{\text{Cs(c)}} - (H_{O}^O)_{\text{Cs}_1(g)} = -18\ 920.0$  calories per mole. Therefore,  $(H_{O}^O)_{\text{Cs}_1(g)} = -1807.2 - (-18\ 920.0) = 17\ 112.8$  calories per mole. From table IV,  $(\Delta H_{O}^O)_2 = -D_O^O = (H_{O}^O)_{\text{Cs}_2(g)} - 2(H_{O}^O)_{\text{Cs}_1(g)} = -10\ 500$  calories per mole. Therefore,

$$(H_{O}^O)_{\text{Cs}_2(g)} = -10\ 500.0 + 2(17\ 112.8) = 23\ 725.6 \quad \text{cal/mole}$$

### Heats of Formation

Two sets of values for heats of formation are given in tables II to IV. The first set (col. 7) is for the formation of the given species from Cs(c),  $(\Delta H_T^O)_f$ ; the second set (col. 9) is for the formation from Cs<sub>1</sub>(g),  $(\Delta H_T^O)$ . For Cs<sub>2</sub>(g) at 298.15° K, for example,

$$(\Delta H_{298.15}^O)_{f,2} = (H_{298.15}^O)_{\text{Cs}_2(g)} - 2(H_{298.15}^O)_{\text{Cs(c)}} \quad (1)$$

TABLE VII. - THERMODYNAMIC PROPERTIES OF CESIUM ON SATURATION LINE

T, °K	P, atm	Partial pressure, atm		x <sub>2</sub> , g/g mixture	M <sub>g</sub> , g/mole	v, cc/g	ρ, g/1000 cc
		p <sub>1</sub>	p <sub>2</sub>				
100	0.700238E-36	0.700238E-36	0	0	132.9100	0.881712E 38	0.113416E-34
200	0.282767E-15	0.282767E-15	0.163606E-22	0.000000	132.9100	0.436690E 18	0.278995E-14
298.15	0.150230E-08	0.150230E-08	0.611635E-13	0.000081	132.9154	0.122528E 12	0.816142E-08
300	0.182308E-08	0.182308E-08	0.804806E-13	0.000088	132.9159	0.101594E 12	0.984309E-08
a301.8	C.219558E-08	0.219547E-08	0.104789E-12	0.000095	132.9163	0.848638E 11	0.117836E-07
a301.8	C.219561E-08	0.219550E-08	0.104792E-12	0.000095	132.9163	0.848626E 11	0.117837E-07
400	0.341969E-05	0.341672E-05	0.296875E-08	0.001735	133.0254	0.721553E 04	0.138590E-04
500	0.295484E-03	0.294083E-03	0.140152E-05	0.009441	133.5404	0.103981E 07	0.961717E-03
600	0.557482E-02	0.549759E-02	0.772344E-04	0.027330	134.7514	0.655416E 05	0.152575E-01
700	0.444664E-01	0.432016E-01	0.126485E-02	0.055316	136.6906	0.945055E 04	0.105814E-00
800	0.208062E-00	0.198266E-00	0.979553E-02	0.089926	139.1674	0.226720E 04	0.441072E-00
900	0.683671E 00	0.637354E 00	0.463169E-01	0.126898	141.9143	0.761201E 03	0.131371E 01
b937.71	0.100008E 01	0.924375E 00	0.757002E-01	0.140736	142.9706	0.538170E 03	0.185815E 01
1000	0.175554E 01	0.159982E 01	0.155720E-00	0.162950	144.6494	0.323037E 03	0.309562E 01
1100	0.37687E 01	0.335835E 01	0.409726E-00	0.196145	147.3621	0.162561E 03	0.615152E 01
1200	0.707012E 01	0.617109E 01	0.899025E 00	0.225626	149.8106	0.929698E 02	0.107552E 02
1300	0.119630E 02	0.102442E 02	0.171877E 01	0.251251	152.0058	0.586644E 02	0.170461E 02
1400	0.186618E 02	0.157093E 02	0.295255E 01	0.273202	153.9381	0.399906E 02	0.250099E 02
1500	0.272819E 02	0.226204E 02	0.466151E 01	0.291861	155.6196	0.259923E 02	0.344919E 02

T, °K	h <sub>c</sub> , cal/g	Δh <sub>vap</sub> , cal/g	h <sub>g</sub> , cal/g	s <sub>c</sub> , cal/(g)(°K)	Δs <sub>vap</sub> , cal/(g)(°K)	s <sub>g</sub> , cal/(g)(°K)	(c <sub>p</sub> ) <sub>eq</sub> , cal/(g)(°K)	(c <sub>p</sub> ) <sub>fr</sub> , cal/(g)(°K)
100	-9.7743	142.2668	132.4925	0.0968189	1.4226679	1.5194868	0.0373794	0.0373794
200	-4.9891	141.2196	136.2305	0.1298676	0.7060981	0.8359656	0.0373801	0.0373794
298.15	0	139.8963	139.8963	0.1501256	0.4692146	0.6193402	0.0375824	0.0373792
a301.8	0.0971	139.8683	139.9653	0.1504492	0.4662276	0.6166767	0.0375969	0.0373792
a301.8	0.1911	139.8410	140.0321	0.1507629	0.4633566	0.6141195	0.0376118	0.0373791
400	4.1043	135.9279	140.0321	0.1637288	0.4503905	0.6141193	0.0376118	0.0373791
500	9.6125	134.0232	143.6357	0.1795298	0.3350579	0.5145876	0.0398111	0.0373752
600	15.2216	131.8333	147.0349	0.1920465	0.2636666	0.4557130	0.0458544	0.0373554
700	20.8306	129.2160	150.0466	0.2022730	0.2153599	0.4176329	0.0541423	0.0373147
800	26.4397	126.1692	152.6089	0.2109194	0.1802417	0.3911611	0.0614825	0.0372601
900	32.0488	122.8336	154.8824	0.2184094	0.1535420	0.3719515	0.0660140	0.0372054
b937.71	37.6578	119.3871	157.0449	0.2250162	0.1376523	0.3576685	0.0676452	0.0371621
1000	39.7735	118.0880	157.8615	0.2273185	0.1259323	0.3532508	0.0676643	0.0371503
1100	43.2676	115.9676	159.2352	0.2309262	0.1159676	0.3468938	0.0671774	0.0371375
1200	48.8767	112.6646	161.5413	0.2362719	0.1024224	0.3386943	0.0654981	0.0371339
1300	54.4857	109.5154	164.0011	0.2411527	0.0912628	0.3324155	0.0632733	0.0371519
1400	60.0948	106.5303	166.6251	0.2456422	0.0819464	0.3275866	0.0609153	0.0371916
1500	65.7039	103.7060	169.4098	0.2497991	0.0740757	0.3238748	0.0586486	0.0372548
	71.3129	101.0281	172.3410	0.2536686	0.0673521	0.3210207	0.0565811	0.0373430

<sup>a</sup>Melting point.<sup>b</sup>Normal boiling point to equilibrium mixture.

$$(\Delta H_{298.15}^{\circ})_2 = (H_{298.15}^{\circ})_{\text{Cs}_2(\text{g})} - 2(H_{298.15}^{\circ})_{\text{Cs}_1(\text{g})} \quad (2)$$

## Equilibrium Constants

Two sets of logarithms of the equilibrium constants for the two formation reactions discussed previously are also listed in tables II to IV. The equilibrium constant  $K_f$  for formation from the assigned reference element (col. 8) is obtained from the standard free energy change  $(\Delta F_{\text{T}_f}^{\circ})$  by means of the equation

$$\log_{10} K_f = - \frac{(\Delta F_{\text{T}_f}^{\circ})}{2.3025851 RT} \quad (3)$$

The equilibrium constant  $K$  for formation from the atomic gas is obtained from a similar equation

$$\log_{10} K = - \frac{\Delta F_{\text{T}}^{\circ}}{2.3025851 RT} \quad (4)$$

Atomic weights, the universal gas constant and the constants used in the evaluation of the entropy constant were the same as those used in reference 1.

## SELECTION OF INITIAL DATA

### Crystal

Heat capacities of the crystal (table I, p. 4) were derived by smoothing the experimental data from the sources given in table VIII.

The following procedure was used to obtain smooth data from 0° to 100° K. A least-squares fit of the data of reference 2 was used in the temperature range from 0° to 4° K. Data from 4° to 20° K were obtained from a curve drawn through the data of reference 2 at 4° K and through the data of references 3 and 4 at 20° K. Data from 20° to 100° K were obtained from a least-squares fit of the data of reference 4 in that temperature range.

Between 100° and 210° K, the data of reference 4 are approximately linear in tem-

TABLE VIII. - REFERENCES FOR HEAT  
CAPACITIES OF CRYSTAL

Temperature range, °K	Source
0.3 to 4 8 to 12	Ref. 2 Private communication from Professor D. C. McCollum of University of California in Riverside, California and ref. 3
20 to 210	Ref. 4

perature. The heat capacities at 100° and 210° K yield the equation

$$C_p^O = 5.76 + 0.004 T \quad (5)$$

Above 210° K, thermal effects associated with the cesium-oxygen system cause anomalous increases in heat capacity and therefore these data were not used. Equation (5) was used to extrapolate heat capacities up to the melting point. The melting point of 301.8° K and the

heat of fusion of 520.1 calories per mole were taken from reference 5.

Reference 4 gives a melting point of 300.5° K and the total heat absorption between the crystal at 262.5° K and the liquid at 300.5° K. If this heat is compared with the sensible enthalpy change of the crystal between these two temperatures, as calculated from equation (5), the implied heat of melting is 514 calories per mole. This value is in reasonable agreement with the value adopted.

The enthalpy from the linear equation for  $C_p^O$ , when combined with the heat of fusion, gave

$$(H_{301.8}^O)_{Cs(liquid)} - (H_{298.15}^O)_{Cs(crystal)} = 545.5 \text{ cal/mole} \quad (6)$$

## Liquid

A number of empirical equations have been used to satisfactorily fit enthalpy data as a function of temperature for various substances; however, heat capacity data derived from differentiation of the enthalpy equations are often very unreliable. For any particular species, various empirical enthalpy equations that might be chosen yield considerably different sets of heat capacities.

Two sets of experimental enthalpy data were considered: that of references 6 and 7. The curve of reference 6 exhibits an anomalous bump from 351° to 620° K, followed by a straight line to 1238° K. It is recommended in reference 6 that just the straight-line portion be used, which has a standard deviation  $\sigma = 1.5$  percent. For the cubic equation (from 340° to 1176° K) of reference 7,  $\sigma = 1.1$  percent.

The implied  $C_p^O = 7.25$  calories per mole per °K of reference 6 differs greatly from the heat capacities derived from the enthalpy curve of reference 7 and listed in table IX.

According to reference 7, the curves of heat capacity against temperature of liquid

TABLE IX. - HEAT CAPACITIES  
DERIVED FROM ENTHALPY  
CURVE OF REFERENCE 7

Absolute temperature, T, °K	Heat capacity at constant pressure for standard state, $C_p^0$ , cal/(mole)(°K)
301.8	10.35
500	7.28
700	6.23
1000	8.53
1200	12.64
1500	22.67

cesium and other alkali metals have a parabolic shape; that is, heat capacity initially decreases with increasing temperature, reaches a minimum, and then increases continuously. However, a parabolic shape for heat capacity of these species is only the result of selecting a cubic to represent experimental enthalpy data.

It was thought advisable to use a straight line for enthalpy because (1) the straight line, in the standard deviation sense, represents cesium enthalpies about as well as the cubic does and (2) the cubic has the disadvantage of implying very large heat capacities for even a few hundred degrees extrapolation.

The actual straight line used in this report was based on the straight-line data of reference 6 but was constrained to go through the previously calculated relative heat content of 545.5 calories per mole at the melting point (eq. (6)). This gives the following equation:

$$(H_T^0)_{\text{Cs(liquid)}} - (H_{298.15}^0)_{\text{Cs(crystal)}} = -1704.5 + 7.455 T \quad (7)$$

Equation (7) implies a constant value of  $C_p^0 = 7.455$  calories per mole per °K.

Had the data of reference 7 been fitted to a straight line and similarly constrained to go through the heat content of 545.5 calories per mole, a constant value of  $C_p^0 = 7.595$  calories per mole per °K would have resulted. The enthalpies would be, on the average, only about 1 percent higher than those derived from the data of reference 6.

The enthalpy data of reference 8 are about 6 to 7 percent lower than the data of both references 6 and 7 over the range from about 600° to 1300° K; therefore, they were not used.

### Monomer (Gas)

The partition function used to compute the thermodynamic properties of  $\text{Cs}_1$  was truncated by the temperature-dependent cutoff technique used in reference 1. The results of these computations are exactly the same up to 2200° K as would be obtained by simply using all levels given in reference 9 with no cutoff. Above 2200° K enthalpy and entropy differ only in the last place computed and heat capacity in the last or second last place.

## Dimer (Gas)

The method used to compute the thermodynamic properties of  $\text{Cs}_2$  is the method for diatomic molecules described in reference 1. The constants for the dimer are shown in table V (p. 8). They were taken from references 10 and 11.

## Vapor Pressures

During the period 1913 to 1937, the investigations reported in references 12 to 18 obtained vapor pressure data for cesium in the temperature range from  $238^\circ$  to  $670^\circ$  K. This early work was evaluated in reference 19 where it was concluded that, except for the results of references 17 and 18, the early work is not too reliable.

The vapor pressures in the  $455^\circ$  to  $589^\circ$  K range (ref. 17) were used in reference 19 to generate a vapor pressure equation. Inasmuch as the data of reference 17 are only relative pressure data (obtained by the magneto-optical method) and are converted to absolute pressure data by relating them to the unreliable data of reference 13, it seems prudent to disregard the data of reference 17.

Recently, the first experimental measurements in the temperature range that included the boiling point ( $742^\circ$  to  $1199^\circ$  K) were reported in reference 20. These data check reasonably well with the later data of reference 6 ( $727^\circ$  to  $1334^\circ$  K).

In view of the previous observations, the data of references 18 (vapor pressures in the liquid range), 20, and 6 were combined and fitted by the least-squares technique. All the data were given the same weight. The results of several empirical equations were compared. The following equation, which is in the form of the Kirchhoff equation, was accepted because it gave as satisfactory results as the other forms considered:

$$\log_{10} P = -\frac{3920.38}{T} + 5.71342 - 0.519781 \log_{10} T \quad (8)$$

If only vapor pressures were considered in this report, then the smoothed experimental vapor pressures obtained from equation (8) would be accepted. As pointed out in the INTRODUCTION, however, these smoothed data, when combined with other thermodynamic data, lead to inconsistencies in the heat of condensation of the monomer at  $0^\circ$  K ( $\Delta H_{O_c}^\circ$ ). Therefore, the data from equation (8) are used only for preliminary analysis, whereas the final recommended vapor pressures are calculated as explained in detail in the section Pressures and Weight Fractions of Gaseous Species.

## Heat of Dissociation at 0° K

An upper bound ( $4020\text{ cm}^{-1}$ ) for the heat of dissociation at 0° K ( $D_{\text{O}}^{\text{O}}$ ) is estimated in reference 21 by analytical extrapolation of the ground state vibrational intervals. A lower bound ( $3318\text{ cm}^{-1}$ ) is estimated in reference 21 by making certain assumptions as to the final states of the excited atoms produced. The average of these two values, which is equivalent to  $10\,500 \pm 1000$  calories per mole of dimer, is recommended in this reference.

The estimate of 0.453 eV or 10 450 calories per mole from the correlation of force constants, equilibrium internuclear distances, and heats of dissociation of the alkali metals is obtained in reference 22. A technique for deducing a value of  $D_{\text{O}}^{\text{O}}$  where  $D_{\text{O}}^{\text{O}}$  was not well known is suggested in reference 23. This technique gave an optimum  $D_{\text{O}}^{\text{O}} = 10\,000$  calories per mole which is in fairly close agreement with the spectroscopic value of 10 500 calories per mole.

The calculation of  $(\Delta H_{\text{O}}^{\text{O}})_{\text{c}}$ , which is discussed in the next section, depends in part on the value of  $D_{\text{O}}^{\text{O}}$ . While no value of  $D_{\text{O}}^{\text{O}}$  that was tried gave a constant value of  $(\Delta H_{\text{O}}^{\text{O}})_{\text{c}}$  over the entire temperature range of 301.8° to 1500° K, values of  $D_{\text{O}}^{\text{O}}$  from about 10 000 to 11 500 calories per mole gave the most nearly constant value of  $(\Delta H_{\text{O}}^{\text{O}})_{\text{c}}$ .

Based on this analysis, the conclusion was that the spectroscopic value was approximately correct, and the value  $D_{\text{O}}^{\text{O}} = 10\,500$  calories per mole was selected.

## Heat of Condensation of Monomer at 0° K

The values of  $(\Delta H_{\text{O}}^{\text{O}})_{\text{c}}$  in calories per mole are given in a number of publications as follows: -19 048 (ref. 24), -18 790 (ref. 19), -19 050 (ref. 25), and -19 035 (ref. 26).

The aforementioned values of  $(\Delta H_{\text{O}}^{\text{O}})_{\text{c}}$  are based on the pre-1962 vapor pressures. Therefore, this report will recommend a "best"  $(\Delta H_{\text{O}}^{\text{O}})_{\text{c}}$  of -18 920 on the basis of the newer vapor pressures, as discussed in the following section.

## THERMODYNAMIC ANALYSIS

As discussed in the INTRODUCTION, the procedure for the selection of a value for  $(\Delta H_{\text{O}}^{\text{O}})_{\text{c}}$  is to find that  $(\Delta H_{\text{O}}^{\text{O}})_{\text{c}}$  for which the difference between the calculated and smoothed experimental vapor pressures is a minimum. As a first step, it is necessary to compute  $(\Delta H_{\text{O}}^{\text{O}})_{\text{c}}$  for each temperature in the range of interest.

### Derivation of $(\Delta H_O^0)_c$

The zero-degree heat of condensation of monomer was computed by means of the relation

$$(\Delta H_O^0)_c = (\Delta F_T^0)_c - \Delta(F_T^0 - H_O^0)_c \quad (9)$$

where

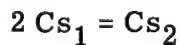
$$(\Delta F_T^0)_c = (F_T^0)_{Cs(c)} - (F_T^0)_{Cs_1(g)} = RT \ln p_1 \quad (10)$$

and

$$\Delta(F_T^0 - H_O^0)_c = (F_T^0 - H_O^0)_{Cs(c)} - (F_T^0 - H_O^0)_{Cs_1(g)} \quad (11)$$

### Partial Pressure of Monomer

The partial pressure of monomer  $p_1$  in atmospheres is obtained from the simultaneous solution of Dalton's Law and the equilibrium-constant equation for the dimerization reaction



The equations are

$$P = p_1 + p_2 \quad (12)$$

and

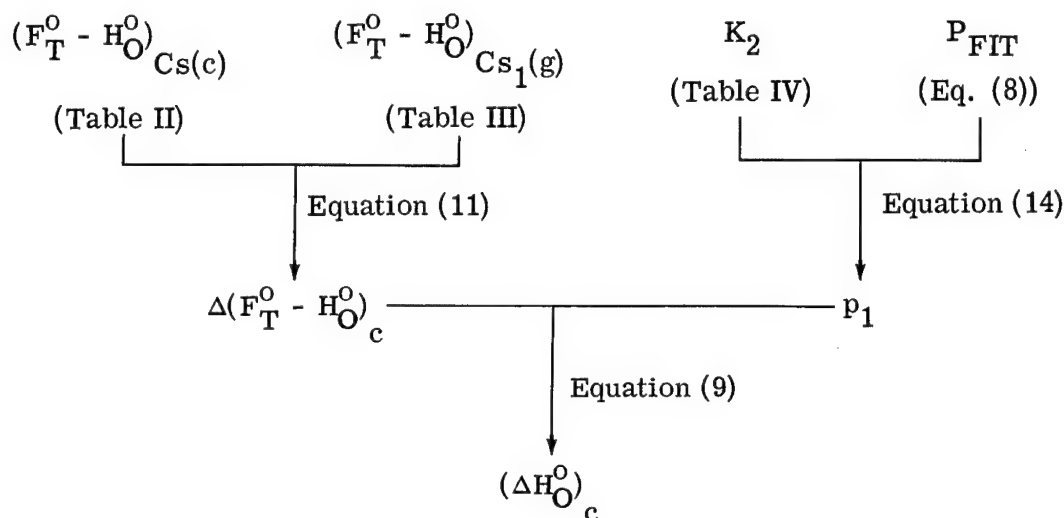
$$K_2 = \frac{p_2}{p_1^2} \quad (13)$$

where  $P$  is the total pressure,  $p_2$  is the partial pressure of dimer, and  $K_2$  is the equilibrium constant of dimerization. Values of  $K_2$  are obtained from table IV (p. 7). The solution of equations (12) and (13) is



$$p_1 = \frac{-1 + \sqrt{4PK_2 + 1}}{2K_2} \quad (14)$$

Therefore, apparent values of  $(\Delta H_{\text{O}}^{\text{O}})_c$  can be computed at every temperature of interest by starting with given values of  $D_{\text{O}}^{\text{O}}$ , values of  $F_{\text{T}}^{\text{O}} - H_{\text{O}}^{\text{O}}$  for monomer, dimer, and condensed phase, and smoothed experimental vapor pressures  $P_{\text{FIT}}$ . This procedure can be summarized as follows:



### RESULTS OF CALCULATING $(\Delta H_{\text{O}}^{\text{O}})_c$

The apparent  $(\Delta H_{\text{O}}^{\text{O}})_c$  values computed by means of this procedure from equation (9) are given in table X. The maximum difference is about 1 percent.

If some single arbitrary value of  $(\Delta H_{\text{O}}^{\text{O}})_c$  is selected, then for each of the previous temperatures there will be a difference between the smoothed experimental vapor pressure  $P_{\text{FIT}}$  and the vapor pressure  $P_{\text{CALC}}$  calculated with this arbitrary  $(\Delta H_{\text{O}}^{\text{O}})_c$  value.

For this analysis, an error function may be defined as  $|P_{\text{FIT}} - P_{\text{CALC}}|/P_{\text{FIT}}$  averaged over the previous number of temperatures. The procedure for selecting a value of  $(\Delta H_{\text{O}}^{\text{O}})_c$  is to find that value of  $(\Delta H_{\text{O}}^{\text{O}})_c$  which gives the minimum error function.

The results of calculating the error function for various values of  $(\Delta H_{\text{O}}^{\text{O}})_c$  are given in table XI. The optimum  $(\Delta H_{\text{O}}^{\text{O}})_c$  was taken to be -18 920 calories per mole to the nearest 5 calories.

The fact that there is still about 4 percent error between the smoothed experimental vapor pressure and vapor pressure calculated with the optimum  $(\Delta H_{\text{O}}^{\text{O}})_c$ , indicates that

TABLE X. - APPARENT VALUES OF  $-(\Delta H_O^0)_c$ 

AS A FUNCTION OF TEMPERATURE

Temperature, T, °K	$-(\Delta H_O^0)_c$ , cal/mole	Temperature, T, °K	$-(\Delta H_O^0)_c$ , cal/mole
301.8	18 791.6	1000	18 965.1
400	18 872.5	1100	18 954.3
500	18 921.7	1200	18 937.0
600	18 949.3	1300	18 913.1
700	18 963.6	1400	18 881.9
800	18 969.7	1500	18 843.4
900	18 970.0		

TABLE XI. - ERROR FUNCTION

FOR VARIOUS VALUES

OF  $-(\Delta H_O^0)_c$ 

$-(\Delta H_O^0)_c$ , cal/mole	Error function, $ \Delta P /P$
18 850	0.0538
18 900	.0397
18 910	.0381
18 920	.0370
18 925	.0370
18 930	.0372
18 950	.0389
18 970	.0458

discrepancies still remain which may be in any of the following data:

(a) Experimental vapor pressures

(b)  $D_O^0$

(c) Molecular constants of dimer (and, consequently, its thermodynamic properties)

(d) Heat content (and other derived thermodynamic properties) of the condensed phase

(e)  $(\Delta H_O^0)_c$

The 4 percent error may also be due, in part, to the presence of a higher polymer, for example, trimer or tetramer; however, this possibility has not been considered in this report.

## CALCULATION OF EQUILIBRIUM MIXTURE PROPERTIES ON SATURATION LINE

As explained in the INTRODUCTION, selection of an optimum value of  $(\Delta H_O^0)_c$  makes it possible to compute a set of vapor pressures consistent with the sensible free energies of the pertinent species. These vapor pressures and other equilibrium properties on the saturation line (e.g., enthalpy, specific heat, and entropy) are given in table VII (p. 9). The equations used to obtain these properties are given in the following sections.

### Pressures and Weight Fractions of Gaseous Species

By starting with the optimized  $(\Delta H_O^0)_c$  and the sensible free energies of monomer and condensed phase, monomer pressure was computed with equations (9) to (11).

Dimer pressure was computed from equation (13). The total pressure  $P_{\text{CALC}}$  was obtained from the sum of  $p_1$  and  $p_2$ .

The weight fraction of monomer  $x_1$  was obtained from the mole fraction of monomer  $N_1$ ; thus,

$$N_1 = \frac{p_1}{P} \quad (15)$$

$$x_1 = \frac{N_1}{2 - N_1} \quad (16)$$

The weight fraction of the dimer  $x_2$  was obtained from the defining equation

$$x_1 + x_2 = 1 \quad (17)$$

### Enthalpy of Vaporization and Entropy of Vaporization

The heat of vaporization in calories per gram from the condensed state to the equilibrium mixture on the saturation line was obtained from

$$\Delta h_{\text{vap}} = \frac{2x_1(\Delta H_T^0)_{f,1} + x_2(\Delta H_T^0)_{f,2}}{M_2} \quad (18)$$

where  $M_2$  is the molecular weight of dimer (265.82 g/mole). The heats of formation are obtained from tables III and IV (pp. 6 and 7).

The entropy of vaporization in calories per gram is obtained from equation (18) by means of

$$\Delta s_{\text{vap}} = \frac{\Delta h_{\text{vap}}}{T} \quad (19)$$

### Enthalpy, Specific Heat, and Entropy of Cesium Vapor

The enthalpy  $h_g$  in calories per gram of an equilibrium mixture can be defined by

$$h_g = \sum_{i=1}^2 \frac{x_i (H_T^O)_i}{M_i} = \sum_{i=1}^2 x_i h_i \quad (20)$$

Equation (20) for saturation conditions gives the same results as the usual equation for the enthalpy of a mixture

$$h_g = h_{\text{vap}} + h_c$$

where  $h_c$  is the enthalpy of the condensed phase in calories per gram (table VII, p. 9).

The equilibrium specific heat at constant pressure in calories per gram per  $^{\circ}\text{K}$  is defined by

$$(c_p)_{\text{eq}} = \left( \frac{\partial h}{\partial T} \right)_p \quad (21)$$

Using equation (20) results in equation (21) becoming

$$(c_p)_{\text{eq}} = \sum_{i=1}^2 x_i (c_p)_i + \sum_{i=1}^2 h_i \left( \frac{\partial x_i}{\partial T} \right)_p \quad (22)$$

or

$$(c_p)_{\text{eq}} = (c_p)_{\text{fr}} + (c_p)_{\text{r}} \quad (23)$$

From equation (17), it follows that

$$\left( \frac{\partial x_1}{\partial T} \right)_p = - \left( \frac{\partial x_2}{\partial T} \right)_p \quad (24)$$

Therefore,

$$(c_p)_{\text{r}} = \left( \frac{\partial x_2}{\partial T} \right)_p (h_2 - h_1) = \left( \frac{\partial x_2}{\partial T} \right)_p \frac{(\Delta H_T^O)_2}{M_2} \quad (25)$$

Values of  $(\Delta H_T^0)_2$  are tabulated in table IV (p. 7). Values of  $(\partial x_2/\partial T)_p$  may be calculated from the following equation:

$$\left(\frac{\partial x_2}{\partial T}\right)_p = \frac{(\Delta H_T^0)_2}{RT^2} \frac{x_2(2 - x_2)(1 - x_2)}{2} \quad (26)$$

Equation (26) may be derived from the following expression, which is equivalent to equation (13):

$$K_2 = \frac{x_2(2 - x_2)}{4P(1 - x_2)^2} \quad (27)$$

and from the van't Hoff isobar, namely,

$$\left(\frac{\partial \ln K_2}{\partial T}\right)_p = \frac{(\Delta H_T^0)_2}{RT^2} \quad (28)$$

The entropy of the gas mixture may be obtained from

$$s_g = \Delta s_{\text{vap}} + s_c \quad (29)$$

where  $s_c$  is the entropy of the condensed phase in calories per gram per  $^{\circ}\text{K}$  (table VII, p. 9) and  $\Delta s_{\text{vap}}$  is obtained from equation (19). Equation (29) gives the identical results as the usual equation for the entropy of a mixture.

### Molecular Weight of Mixture

An expression for the molecular weight of the mixture  $M_g$  (in g/mole) in terms of the molecular weight and weight fraction of the dimer may be obtained as follows:

$$M_g = \frac{1}{n} = \frac{1}{n_1 + n_2} = \frac{1}{\frac{x_1}{M_1} + \frac{x_2}{M_2}} = \frac{M_2}{2 - x_2} \quad (30)$$

where  $n$ ,  $n_1$ , and  $n_2$  are the number of moles of mixture, monomer, and dimer per gram of mixture, respectively.

### Specific Volume and Density of Mixture

The specific volume  $v$  in cubic centimeters per gram may be obtained from the ideal gas law

$$v = \frac{RT}{PM_g} = \frac{82.05971 T}{PM_g} \quad (31)$$

The density  $\rho$  in grams per 1000 cubic centimeters is, therefore,

$$\rho = \frac{1000}{v} \quad (32)$$

## DISCUSSION OF VAPOR PRESSURES

### Vapor Pressures Above Liquid

Table VI contains boiling points of liquid cesium at saturation pressures from  $10^{-8}$  to 10 atmospheres at every power of 10. These data were calculated in two ways:

- (1) From the recommended thermodynamic data, as explained in the section  
THERMODYNAMIC ANALYSIS
- (2) By a least-squares equation fitted to the recommended  $P_{\text{CALC}}$  values with a standard deviation of 0.5 percent

$$\log_{10} P_{\text{atm}} = \frac{-4053.30}{T} + 7.04453 - 0.915282 \log_{10} T \quad (33)$$

On the average the two sets of boiling points differ by about  $0.2^\circ \text{K}$ . It should be emphasized that the vapor pressure equation (eq. (33)) is recommended rather than equation (8).

Figures 1 and 2 compare the experimental vapor pressures of liquid cesium with a curve drawn through the recommended vapor pressures. The agreement of the two sets is seen to be very good. Figure 1 covers the temperature range from  $303^\circ$  to  $1334^\circ \text{K}$ . Figure 2 covers only the range from  $729^\circ$  to  $1334^\circ \text{K}$  to facilitate detailed comparison.

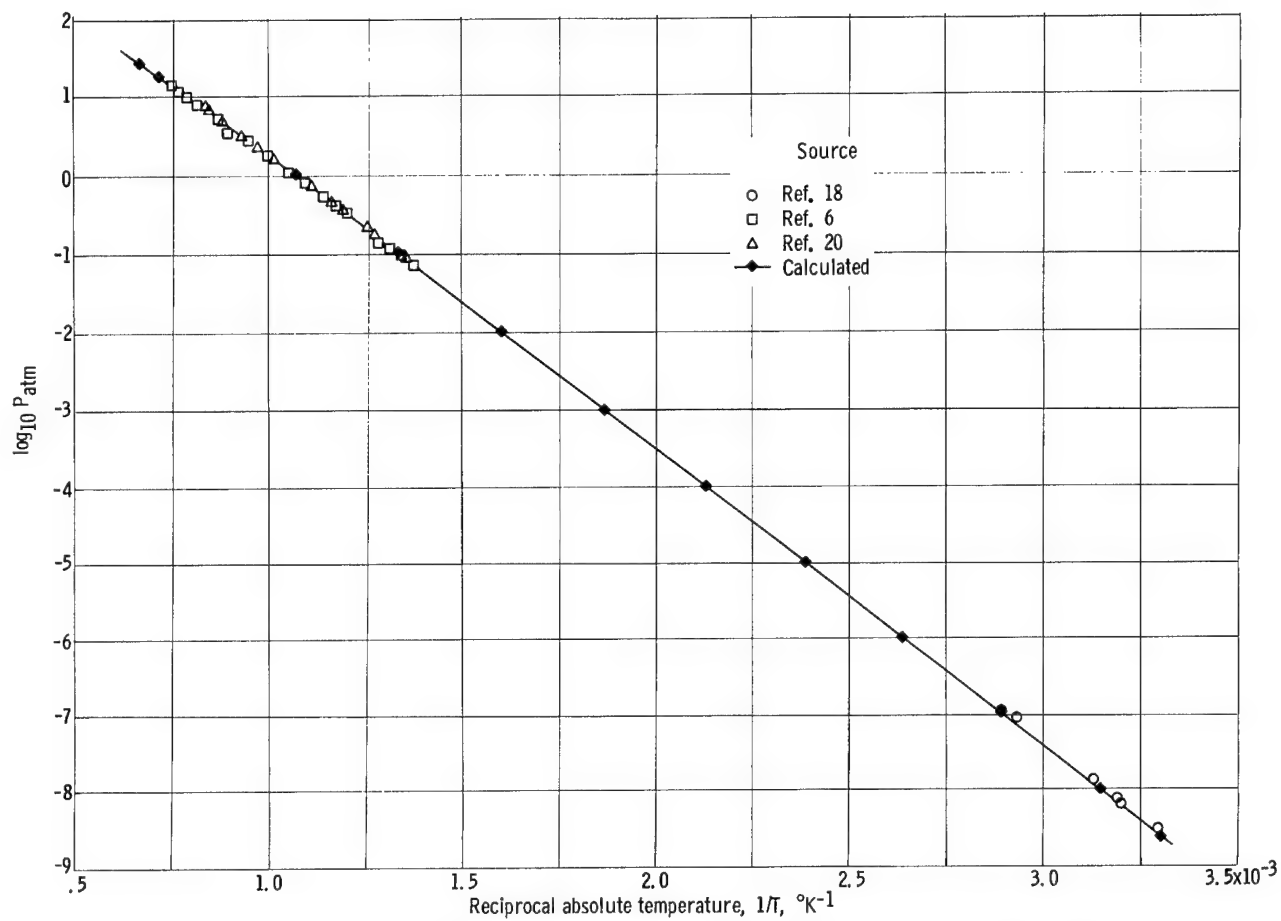


Figure 1. - Comparison of experimental and calculated vapor pressures above liquid cesium (303° to 1334° K).

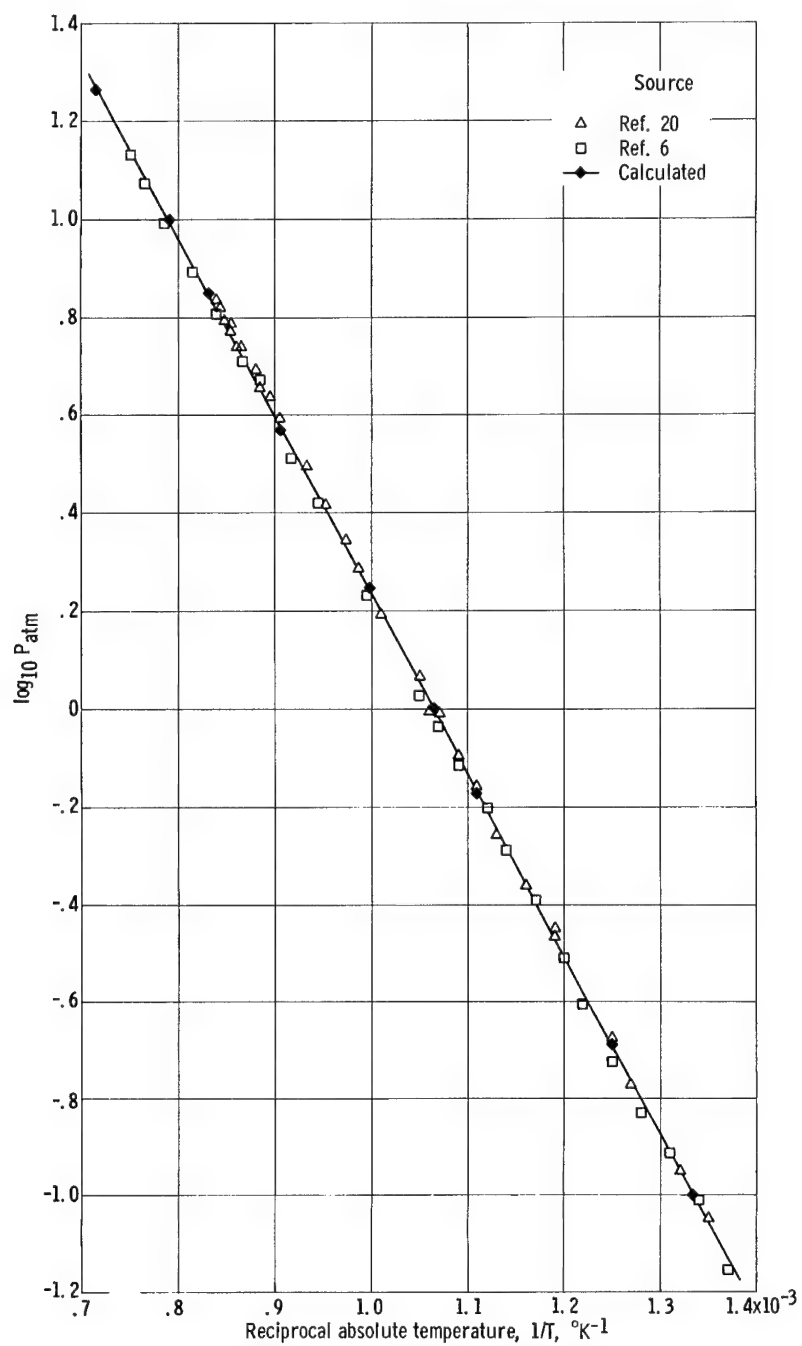


Figure 2. - Comparison of experimental and calculated vapor pressures above liquid cesium (729° to 1334° K).



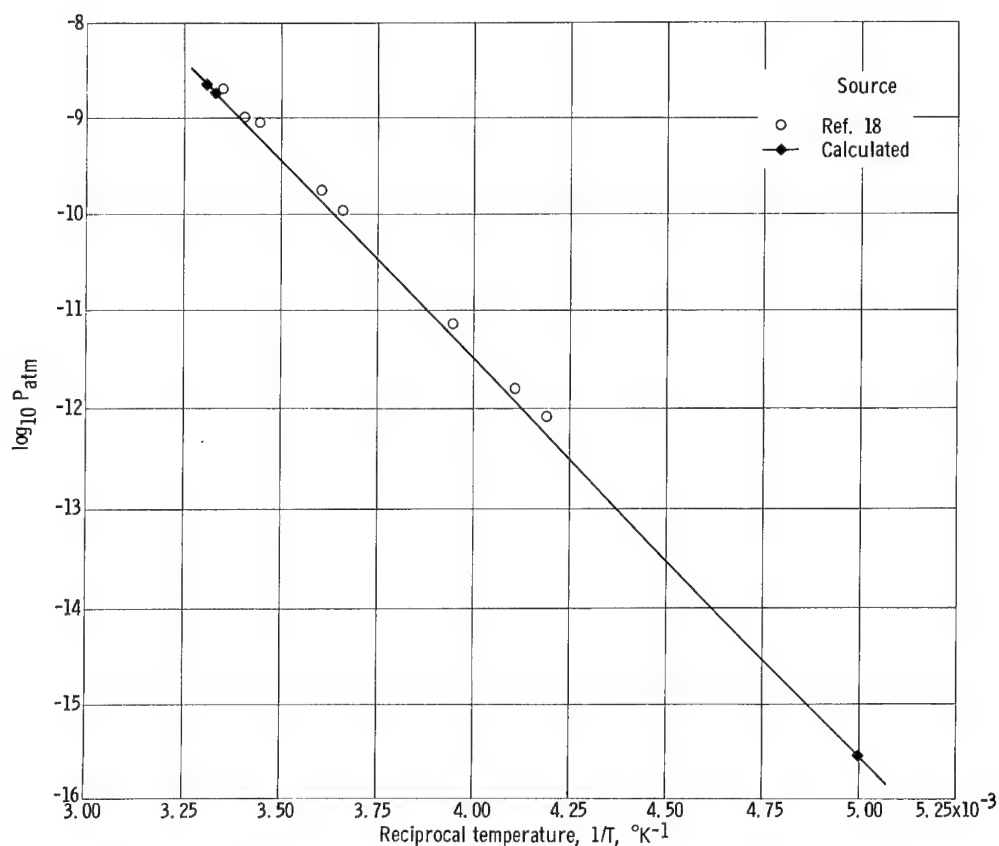


Figure 3. - Comparison of experimental and calculated vapor pressures above crystalline cesium.

Subsequent to the completion of the analysis, a vapor pressure equation in the temperature range  $928^{\circ}$  to  $1558^{\circ}$  K was presented in reference 27. On the average, these vapor pressures are about 2 percent lower than those recommended in this report.

### Vapor Pressures Above Crystal

Experimental vapor pressures above the crystal are available from reference 18 at temperatures from  $238^{\circ}$  to  $298^{\circ}$  K. In order to be consistent with the thermodynamic data adopted for this report, however, vapor pressures from  $100^{\circ}$  to  $301.8^{\circ}$  K were calculated in the same manner as were the vapor pressures above the liquid.

On the average, the calculated vapor pressures between  $238^{\circ}$  and  $298^{\circ}$  K were 30 percent lower than the experimental ones (fig. 3). This difference is not significant, however, inasmuch as at the low pressure levels involved, the average difference is only in the order of  $10^{-9}$  atmosphere. Furthermore, the lower calculated vapor pres-

tures are consistent with the assumption of reference 26 that the experimental vapor pressures are too high.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, April 26, 1965.

# APPENDIX - SYMBOLS

$B_e$	rotational constant, $\text{cm}^{-1}$	$(\Delta H_T^0)_f$	enthalpy change for formation of substance from assigned reference element, cal/mole
$C_p^0$	heat capacity at constant pressure for standard state, $\text{cal}/(\text{mole})(^0\text{K})$	$H_O^0$	chemical energy at $0^0\text{ K}$ for standard state, cal/mole
$(c_p)_{eq}$	equilibrium specific heat at constant pressure of mixture, cal/g	$h$	enthalpy, cal/g
$(c_p)_{fr}$	frozen specific heat at constant pressure of mixture, cal/g	$\Delta h_{vap}$	heat of vaporization to 1 gram of equilibrium vapor
$(c_p)_r$	reactive specific heat at constant pressure of mixture, cal/g	$K$	equilibrium constant for reaction of formation from element in atomic gas state
$D_e$	spectroscopic constant for rotational stretching, $\text{cm}^{-1}$	$K_f$	equilibrium constant for reaction of formation from assigned reference element
$D_O^0$	dissociation energy at $0^0\text{ K}$ , cal/mole	$M$	molecular weight based on chemical scale of natural oxygen, g/mole
$F_T^0$	Gibbs free energy for standard state, cal/mole	$N_i$	mole fraction of $i^{\text{th}}$ species, moles of $i^{\text{th}}$ species per mole of mixture
$F_T^0 - H_O^0$	sensible free energy for standard state, cal/mole	$n$	number of moles per gram of equilibrium mixture
$H_T^0$	sum of sensible enthalpy at $T^0\text{ K}$ and chemical energy at $0^0\text{ K}$ for standard state, cal/mole	$P$	total vapor pressure, atm
$H_T^0 - H_O^0$	sensible enthalpy for standard state, cal/mole	$p_i$	partial pressure of $i^{\text{th}}$ species, atm
$\Delta H_T^0$	enthalpy change for formation of substance from element in atomic gas state, cal/mole	$R$	universal gas constant, $1.98726\text{ cal}/(\text{mole})(^0\text{K})$ or $82.05971\text{ (cc)(atm)}/(\text{mole})(^0\text{K})$
		$S_T^0$	entropy for standard state, $\text{cal}/(\text{mole})(^0\text{K})$

$s$	entropy, cal/(g)(°K)	$\omega_e$	zero-order vibrational frequency for diatomic molecule, $\text{cm}^{-1}$
$\Delta s_{\text{vap}}$	entropy of vaporization to 1 gram of equilibrium vapor	$\omega_e^x, \omega_e^y$	anharmonicity constants for diatomic molecule, $\text{cm}^{-1}$
$T$	absolute temperature, °K	Subscripts:	
$v$	specific volume of vapor, cc/g		
$x_i$	weight fraction of $i^{\text{th}}$ species, g of $i^{\text{th}}$ species per g of mixture	$c$	condensed phase property
$\alpha_e$	vibration-rotation interaction constant for diatomic molecule, $\text{cm}^{-1}$	$f$	formation from assigned reference element
$\rho$	density of vapor, g/1000 cc	$g$	property of equilibrium vapor mixture
$\sigma$	standard deviation	$1$	monomer property
		$2$	dimer property

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